Rethinking the Area of Protection “Natural Resources” in Life Cycle Assessment

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# Rethinking the Area of Protection "Natural Resources" in Life Cycle Assessment

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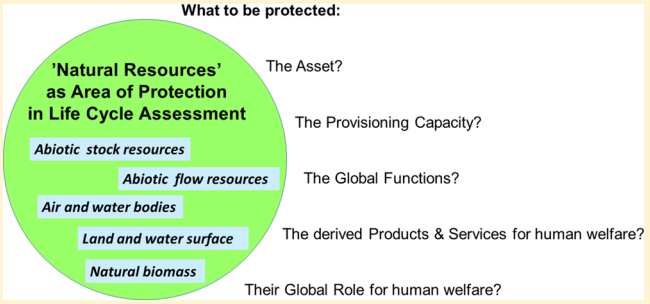
Supporting Information

**ABSTRACT:** Life cycle impact assessment (LCIA) in classical life cycle assessment (LCA) aims at analyzing potential impacts of products and services typically on three so-called areas of protection (AoPs): Natural Environment, Human Health, and Natural Resources. This paper proposes an elaboration of the AoP Natural Resources. It starts with analyzing different perspectives on Natural Resources as they are somehow sandwiched in between the Natural Environment (their cradle) and the human-industrial environment (their application). Reflecting different viewpoints, five perspectives are developed with the suggestion to select three in function of classical LCA. They result in three safeguard subjects: the Asset of Natural Resources, their Provisioning Capacity, and their role in Global Functions. Whereas the Provisioning Capacity is fully in function of humans, the global functions go beyond provisioning as they include nonprovisioning functions for humans and regulating and maintenance services for the globe as a whole, following the ecosystem services framework. A fourth and fifth safeguard subject has been identified: recognizing the role Natural Resources for human welfare, either specifically as building block in supply chains of products and services as such, either with or without their functions beyond provisioning. But as these are far broader as they in principle should include characterization of mechanisms within the human industrial society, they are considered as subjects for an integrated sustainability assessment (LCSA: life cycle sustainability assessment), that is, incorporating social, economic and environmental issues.




## 1. INTRODUCTION: NATURAL RESOURCES AS ONE OF THE AREAS OF PROTECTION

Life cycle impact assessment (LCIA) is defined as the phase of life cycle assessment (LCA) "aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system throughout the life cycle of a product".[1] In their review, Finnveden et al.[2] explain the role of so-called areas of protection (AoPs) in LCIA: "The LCIA should interpret the inventory results into their potential impacts on the areas of protection, that is, the entities that we want to protect. Today, there is acceptance in the LCA community that the protection areas of life cycle assessment are human health, natural environment, natural resources, and to some extent man-made environment".

It is worth to critically have a look at this AoP approach. Two points can be raised. First, whereas classical LCIA aims at evaluating the potential "environmental" impacts, it is obvious that the scope of the aforementioned AoPs is broader than just "environmental": Human Health is beyond "environmental" in sensu stricto. This is equally valid for the fourth AoP proposed by de Haes et al.:[3] man-made environment.

The concept of AoP can be interpreted as an approach that assists in making sustainability more concrete: it helps in defining what safeguard subjects we like to sustain or protect and which impacts should be assessed and modeled.[4] Hence, it may serve as a basis for developing impact assessment not solely from an environmental point of view, but also socio-economically. The idea to expand the AoP concept beyond environment considerations toward social LCIA has indeed been raised, for example, by Dreyer et al.[5] who suggested human dignity and well-being as a new AoP for social LCIA. An additional example is the millennium ecosystems assessment where the interrelations in between the environment with its

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resulting ecosystem services and constituents of well-being are identified.[6]

Based on these observations, that is, the current AoPs in LCIA going beyond environmental considerations in sensu strictu and new AoPs being defined for social LCIA, a more holistic view on AoPs is developed in Figure 1. Here, AoPs are

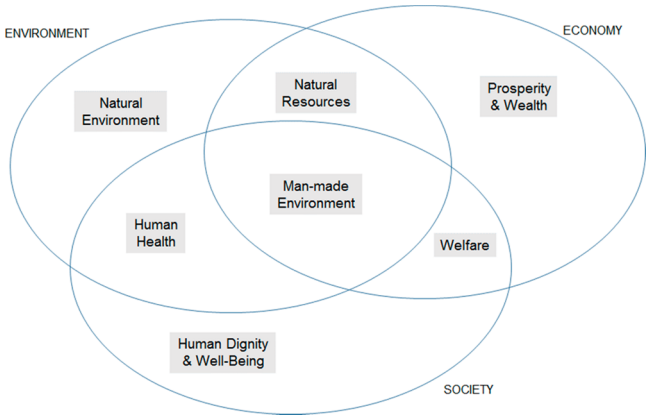


**Figure 1.** Situating areas of protection beyond classical life cycle impact assessment: (1) Positioning of current areas of protection in classical life cycle impact assessment within the three pillars of sustainability: Natural environment (which is suggested to be renamed into ecosystem health); natural resources; human health and man-made environment (environment, economy, society); (2) suggestions for areas of protection exclusively assigned to the pillars of economy (prosperity and wealth) and society (human dignity and well-being and future generations), and to both economy and society (welfare).

proposed that can serve to include environmental, social and economic LCIA, which may lead to life cycle sustainability assessment (LCSA).[7] It comprises the four AoPs of classical LCIA (Natural Environment, Natural Resources, Human Health and Man-Made Environment), but they are not all exclusively assigned to classical LCIA. Indeed, Human Health is an AoP that can also be interpreted as being part of social LCIA; natural resources are essential for economic development: they can hence be seen as an AoP within social and economic LCIA as well. Also the man-made environment, which has been poorly addressed in environment-focused LCIA, can be seen as a common AoP for Social, Environmental and Economic LCIA. Further on, natural environment is typically viewed from the ecosystem quality aspect,[7] not from the base of natural resources; hence the AoP Natural Environment does not include natural resources in the viewpoint of the LCA community. However, this is debatable as in principle natural resources are inherently part of the Natural Environment. In fact, LCA practitioners typically position cause-and-effect chains that impact the "health" of ecosystems under "natural environment" while the provisioning role of the natural environment is considered under "Natural Resources". Therefore, we may suggest to modify the terminology of the AoP "natural environment" into "ecosystem health".

The goal of this figure is not to develop a full set of AoPs for economic and social LCIA, but to raise the idea to use AoPs for integrated LCIA. In this sense, first ideas of AoPs exclusively attributed to social and economic LCIA are suggested: human dignity and well-being and future generations for sLCIA and prosperity and wealth for economic LCIA, and welfare for both social and economic LCIA.

Regarding AoPs commonly used in LCIA: natural environment, human health and natural resources, the ILCD handbook[8−10] proposed indicators for expressing impact on these specific AoPs. With respect to human health, stressors are suggested to be quantified by the DALY (Disability Adjusted Life Years) indicator, being a well-established reference indicator for human impacts also beyond the LCA community (e.g., it is a reference indicator for the World Health Organization[11]). With respect to the AoP Natural Environment—explicitly excluding the resource base function of the environment—it is recommended to quantify the negative effects on ecosystems as a consequence of elementary flows, that is, exposure of the ecosystems to chemicals or physical interventions, by for example, the potentially disappeared fraction of species (PDF). Also this recommendation relies on relatively well established modeling of the impact of elementary flows onto this AoP; however current practice remains limited to many but not all substances.

What the ILCD Handbook does not propose is a recommendation to quantify the impact of elementary flows on the AoP Natural Resources at end point level. Here, the handbook rather brings a discussion on this AoP, concluding that "there are many possibilities in defining the AoP of Natural Resources". The specific section of the Handbook ends with a set of elements to consider:

- *Is this AoP restricted to the role of resources for humans, or does it also include the role of ecosystems [...]? [...]*
- *Is the role of natural resources for humans restricted to its present uses or should we also address future needs? [...]*
- *Are the resources we distinguish for human needs focused on essential functions [...]? [...]*
- *To what extent do we need to address developments in population growth and affluence in the future? [...]*

The objective of this article is to contribute to a better elaboration of the AoP Natural Resources, which should provide a new framework to evaluate LCIA characterization models that are used or should be developed in classical LCA and eventually in LCSA with respect to natural resources. Essentially, the paper focuses on the first question mentioned above; the other questions focus on particular elements that follow from an in-depth answer on the first question. To do so, we first analyze what could be included in the concept of "natural resources". Second, we propose a number of perspectives on natural resources as they can be viewed from many perspectives, that is, from just the asset in the Natural Environment over their services (e.g., see the ecosystem services concept[12]) to a full anthropocentric perspective. Subsequently, a number of perspectives are selected that may match with classical LCA to identify safeguard subjects for the AoP Natural Resources. Finally, these safeguard subjects are further detailed and some suggestions for prioritization in function of needs of characterization models for LCIA are proposed. The paper ends with a first analysis of currently used LCIA characterization models in function of their capability to cover impact on the proposed safeguard subjects.

## 2. NATURAL RESOURCES: DEFINITION OF THE AOP WITHIN DIFFERENT PERSPECTIVES

**2.1. Natural Resources: What Is to Be Covered?** First of all, it has to be clarified what is meant by natural resources. Natural resources can be defined as materials occurring in nature used and transformed by ecosystems and humans, as


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studied by ecology.[13] The concept could be approached from an anthropocentric point of view, for example, by the OECD: "Natural resources are natural assets (raw materials) occurring in nature that can be used for economic production or consumption". However, some sources consider natural resources broader than just raw materials, for example, the Dynamix project[14] defines resources broader to be in line with the EU thematic strategy on the sustainable use of natural resources[15] and the Roadmap for a resource-efficient Europe.[16] Here, natural resources are not only an input used or modified to create economic value, but they are also all environmental media and processes that can be affected by the production, use and disposal of economic goods and services. In fact this latter matches also with "natural environment" as AoP in LCIA. So in view of separating natural resources from natural environment/ecosystem health as an AoP in LCIA, the OECD definition fits quite well as a basis for understanding "natural resources" as an AoP in LCA. This is in line with the review of Bare and Gloria[17] on LCIA approaches, mentioning that natural resources (both abiotic and biotic), "pertains to materials that are extracted, harvested, or otherwise obtained from the environment for beneficial use by humans".

There have been many ways to subdivide the natural resources, for example, biotic versus abiotic, renewable versus nonrenewable, exhaustible versus nonexhaustible, flows versus stocks versus funds.[8−10,18] In the latter, stocks or deposits are resources that are not regenerated within human lifetimes. Examples are fossil fuels, minerals, sediments, clay, etc. Funds are resources that can be regenerated within human lifetimes, for example, groundwater and natural biomass. Flows are resources that are constantly (re)generated, such as wind and solar energy. Basically, natural resources as primary resources (versus wastes as secondary resources) may have a three-dimensional (volume) or a two-dimensional nature (surface). Three dimensional resources can be extracted from

- Soil and sediments (lithosphere), for example, minerals, fossils
- Aquatic bodies (freshwater and seawater) (hydrosphere), for example, underground water, biota
- Atmosphere, for example, particular gases.

On top of these volume-based resources, terrestrial and aquatic surfaces (two-dimensional) are available, for example, harvesting area of natural biomass, biomass production surface (agriculture and forestry) or infrastructure (residential area, industrial area, transport infrastructure) (Table 1). When not really occupied by mankind, the terrestrial and aquatic surfaces (natural land, rivers and estuaries, lakes and wetlands, sea surface) comprise the in situ ecosystems. These surface-dependent ecosystems can be further detailed in terms of their specific abiotic characteristics (climate, geography, physical gradients, mass, concentrations of its components) and biotic population (biomes, species, genetic pool). This can become particularly relevant at a more detailed scale of analysis.

In its broadest sense, LCIA characterization models for Natural Resources should be capable to cover all these Natural Resources.

**2.2. Different Perspectives on Natural Resources.** When putting the question: "what do we like to protect with respect to natural resources?" and hence "what should be assessed in LCIA when it comes to natural resources?", many ways and paths can be taken, depending on the perspective and the role assigned to natural resources. The development of different perspectives has been already presented in literature (e.g., see Steen[19]) but with a narrower scope.

**Table 1. Inventory of Natural Resources, Grouped According to Their Origin: Volumes (Three Dimensional) and Surfaces (Two dimensional)**

| volumes (3D): | | natural resource assets: |
|---|---|---|
| lithosphere | soil and sediments | minerals and materials |
| | | metal ores (incl. nuclear) |
| | | fossil fuels (conventional, unconventional) |
| | | geothermal |
| hydrosphere | freshwater | rain water |
| | | fresh underground water |
| | | fresh surface water (bulk) |
| | | freshwater biota (natural) |
| | | freshwater currents |
| | seawater | marine water (bulk) |
| | | marine biota (natural) |
| | | marine elements (salts...) |
| | | marine currents |
| atmosphere | air | atmospheric gases (He, $CO_2$...) |
| | | wind |
| surfaces (2D): | | |
| terrestrial | land surface[a] | residential/industrial/Transport infrastructure land |
| | | agricultural land |
| | | forestry land |
| | | natural land[b] |
| | | solar irradiation[c] |
| | | terrestrial biota (natural) |
| aquatic | freshwater surface | rivers and estuaries[b] |
| | | lakes and wetlands[b] |
| | | solar irradiation[c] |
| | seawater surface | sea surface (coastal, shelf, deep sea)[b] |
| | | solar irradiation[c] |

[a]Land assets are split into urban, agricultural, forestry etc.; however, some can be multifunctional as well. [b]This includes the natural ecosystems with their services. [c]Solar irradiation is not the land or aquatic surface as such, but solar irradiation as natural resource asset is inherently connected and dependent on surface area.

In Figure 2, five perspectives are represented, starting from the role natural resources play for human welfare in a direct and indirect way. The five perspectives result in five ways to define Safeguard Subjects for the AoP Natural Resources:

*Perspective 1.* Asset of natural resources as safeguard subject (S1): this is a perspective in which natural resources are seen as safeguard subject as such as we are conscious that in the end they have a function for humans directly or indirectly, irrespective of their further role, function or impact on humans and ecosystems. For example, we may consider wood from tropical forests as a particular asset of natural resources irrespective of how they might be used and/or the purpose they serve.

The consequences of adopting Perspective 1 for selecting or developing LCIA methods are manifold. First, it requires an evaluation of what assets should be considered, ranging from an inclusive list following Table 1, or a selection in function of particular assets that need specific protection, for example, nonrenewables because of lack of regeneration. A proper physical quantification of the reduction of the assets in terms of


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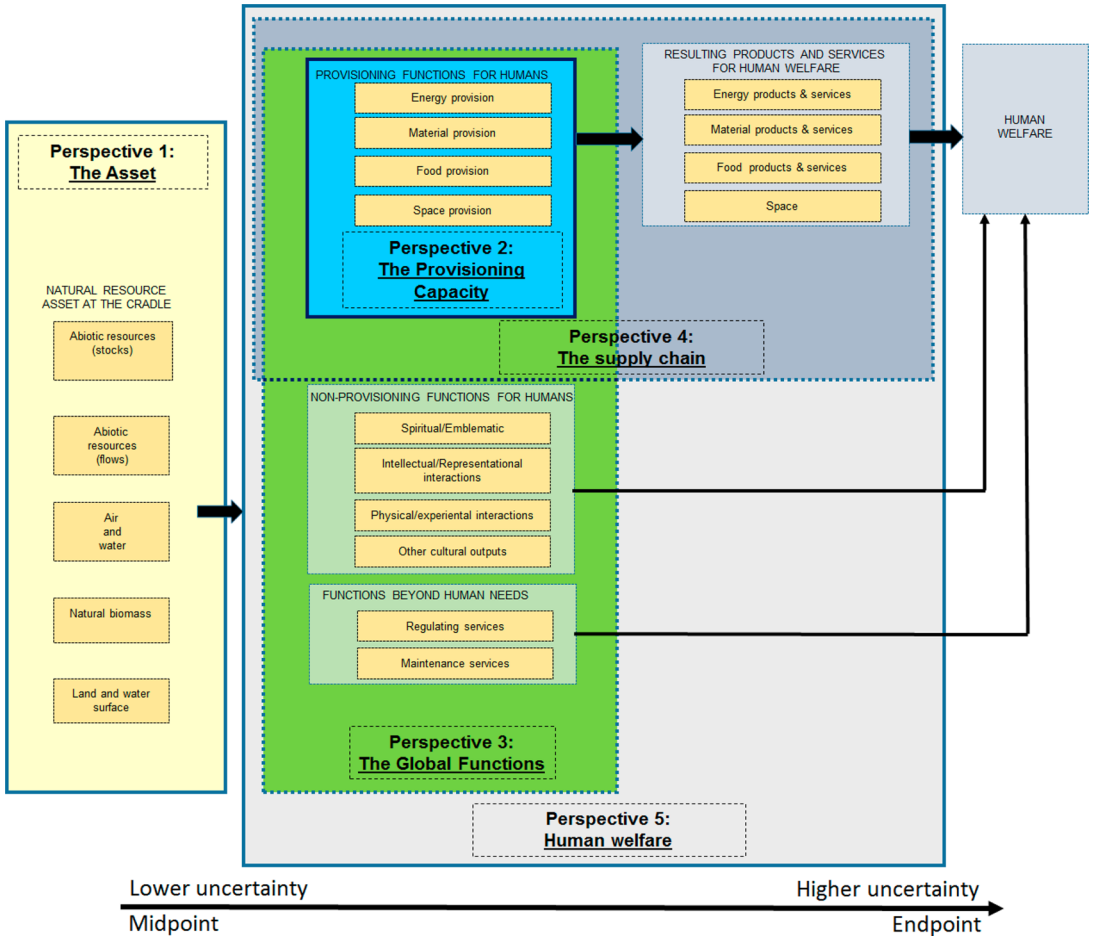


**Figure 2.** Different perspectives on Natural Resources in function of defining safeguard subjects for the AoP Natural Resources in LCIA. Perspective 1 encompasses the yellow box; Perspective 2 the blue box; Perspective 3 the green box (including blue box of Perspective 2); Perspective 4 the dark gray box, including the blue box (Perspective 2); Perspective 5 the light gray box.

mass, volume or area due to the extraction and occupation will be essential to see how the assets are affected. LCIA models might be rather simple without too many assumptions, but not able to link the asset reduction in relation with consequences for human welfare.

*Perspective 2.* Provisioning capacity of natural resources as safeguard subject (S2): this perspective reflects the capacity of ecosystems to fulfill provisioning functions for humans, that is, provide materials, energy, food, and space directly, matching with the so-called provisioning services in the ecosystem services framework[12]. Coming back to the wood from tropical forests as an example, we may define the wood provisioning capacity of forests for construction materials and furniture as particular safeguard subject.

A consequence of adopting Perspective 2 is the need for a proper modeling of the production capacity of the ecosystems relative to human demand. The capacity of the ecosystems depends very much on the nature of the resources. Whereas for flows it is not much an issue as they are in principle continuously (re)generated, it is more peculiar for funds like groundwater and biomass that we may deplete or exterminate. Even more peculiar are stocks: typically the "easiest" ones are exploited first (all other operational conditions being equal), for example, high ore grade deposits: it has been shown that on average the quality of assets in terms of ore grade goes down with time.[20]

*Perspective 3.* Global functions: Natural Resources as essential constituents of Ecosystems as safeguard subject (S3). This perspective recognizes that natural resources are essential subparts of ecosystems and in their functioning: ecosystems with its subparts provide various functions according to the ecosystems framework. These functions can result in ecosystem services that provide a far broader range of services for the global (eco)systems than only provisioning functions for humans. With the example of wood from tropical forests, we may see the role of a forest not only in terms of wood provisioning but also as habitat for tropical fauna and its role in climate regulation.

This perspective requires insights in the consequences of natural resource extraction not only for future natural resource provision, but also on consequent changes in other ecosystem services (nonprovisioning services), for example, climate regulation, water purification, recreation, and tourism.[21] These long-range cause and effect chains are traditionally not handled in LCA practices.

*Perspective 4.* Natural Resources as building block in the supply chain of products and services for human welfare as safeguard subject (S4): as Natural Resources are the backbone of (physical) products and services being essential for human welfare, we can consider them within this anthropocentric point of view. This safeguard subject includes the essential provisioning capacity of the natural resource base (Perspective


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2) but it is expanded in Perspective 4, since a number of socio-economic mechanisms can hinder the human welfare benefits from natural resources. Essentially it covers the full supply chain starting from the elementary flows in Perspective 2 and considers subsequent steps in the supply chain toward the final result from natural resources: products and services for human welfare. This perspective clearly goes beyond environmental and health considerations of classical LCA; it needs characterization of market and socio-economic mechanisms as well, for example, the security of supply concept. For the example of wood from tropical forests, we may be concerned about the impacts on human welfare as a consequence of relying on tropical wood as natural resource for construction materials, for example, through poor working conditions in the supply chain.

Adopting Perspective 4 means LCIA methods should rely not only on quantification of natural resources transferred from the natural environment toward the human industrial environment. Basically, this perspective forces us to think on all kinds of impacts natural resources and their subsequent raw materials and end products have along the provisioning chain. Due to the provisioning role of natural resources, impacts on human welfare could result from resources being conflict minerals, playing a role in geopolitical strategies, labor conditions, or market instabilities.[22]

*Perspective 5.* Natural resources for human welfare as safeguard subject (S5): This is a more holistic point of view on the role natural resources play in human welfare through their direct and indirect functions they provide, encompassing Perspectives 2, 3, and 4. It does include the direct functions humans experience through the provisioning services, hence including Perspective 2 and 3, but also through nonprovisioning functions. It also covers functions beyond immediate human needs, indirectly also relevant for human welfare (Perspective 3). Coming back to wood from tropical forests as a natural resource, we may envisage impacts on human welfare as a result of the products (construction materials), on future provisioning capacity and impacts along the supply chain (working conditions), but also on the spiritual or emblematic value for the local population, or on the global population as they it may affect climate regulation functions.

LCIA methods following Perspective 5 would require multidisciplinary and far going modeling of effects of natural resource extraction, including effects on ecosystem services (Perspective 3) and socio-economic consequences impacting human welfare (Perspective 4).

The different perspectives may be selected in function of the users. For example, a classical LCA focusing on a specific product might be better served with S1, S2, and S3 as safeguard subjects, whereas more integrated LCA at meso or macro scale, especially in a consequential assessment, may have interest in S4 and S5. At the same time, moving from left to right in Figure 2 shifts the impact from the midpoint to the end point and makes the cause-and-effect chains and impact pathways more complex and brings more uncertainty at the same time.

**2.3. Selection of perspectives and Safeguard Subjects for the AoP in Function of Classical LCA.** The above-mentioned sections have shown that different definitions of natural resources exist. From the analysis of their role and functions, five perspectives have been proposed. In function of developing the AoP Natural Resources for LCA, a selection needs to be made. According to current formulations in ISO 14040, LCA "addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)", recognizing that LCA is "one of several environmental management techniques" and that "LCA typically does not address the economic or social aspects of a product". This ISO framework could be considered to push the AoP into an environmental context; however, as is clear from above there is also inherently a "non-environmental aspect" about natural resources. In a way natural resources illustrate how broad or narrow LCA should be interpreted: from "environmental LCA" to an LCSA management tool. A compromise between the focus implied in the context of an ISO 14040 LCA and the broader considerations inherently attached to Natural Resources is to be made.

We may propose that Perspective 4 and Perspective 5 are beyond classical LCA, as they clearly require the analysis of cause and effect chains not only linked to physical elementary flows at the natural environment/human-industrial environment interphase, but also analysis of interactions within the human-industrial environment. Perspectives 1, 2, and 3 are more centered on the elementary flows, hence offering a frame to relate consequences of elementary flows with safeguard subjects in the AoP Natural Resources. Clearly, Perspectives 4 and 5 might be useful when one aims at an integrated LCA, that is, LCSA with coverage of environmental, social and economic issues at the same time.

This reasoning leads to three safeguard subjects for defining the AoP Natural Resources within an environmental LCA context:

- Asset of Natural Resources (S1)
- Provisioning Capacity of Natural Resources (S2)
- Role in Global Functions of Natural Resources (S3)

The safeguard subjects are quite broadly defined and are composed of specific safeguard subjects (SSs), for example, see Table 1 for S1. This may lead to the necessity of many characterization factors and models if one aims at a full impact assessment of a product system on the AoP Natural Resources. Hence, some prioritization might need to be proposed, for example, at the level of the goal and scope of an LCA study or in certain schemes for different policy applications. A number of prioritization criteria can be suggested.

Moreover, the perspective of the LCA practitioner is important; he or she might: (i) like to assess the impact on the asset (Perspective 1), (ii) aim at assessing the impact on the provisioning capacity (Perspective 2) or (iii) the impact on their role in global functions (Perspective 3). A second criterion might the specific safeguard subject (SS): from the specific nature of the Natural Resources and the quantities the human-industrial society relies on some of them, some SSs might be more relevant than others in terms of impact. For example, nonrenewable assets might be of higher priority than renewable ones when it comes down to "energy provision capacity" as specific safeguard subject. Further on, prioritization can be done according to the function: the study may be oriented to some particular ones, for example, impact on food provisioning. Finally, the spatial and temporal scale may be a criterion for the prioritization: the LCA practitioner might like to assess the impact locally or globally, and/or on the shorter or longer term.

A further detailing of the Safeguard Subjects and first thoughts on prioritization is presented in the Supporting Information (SI) SI1.



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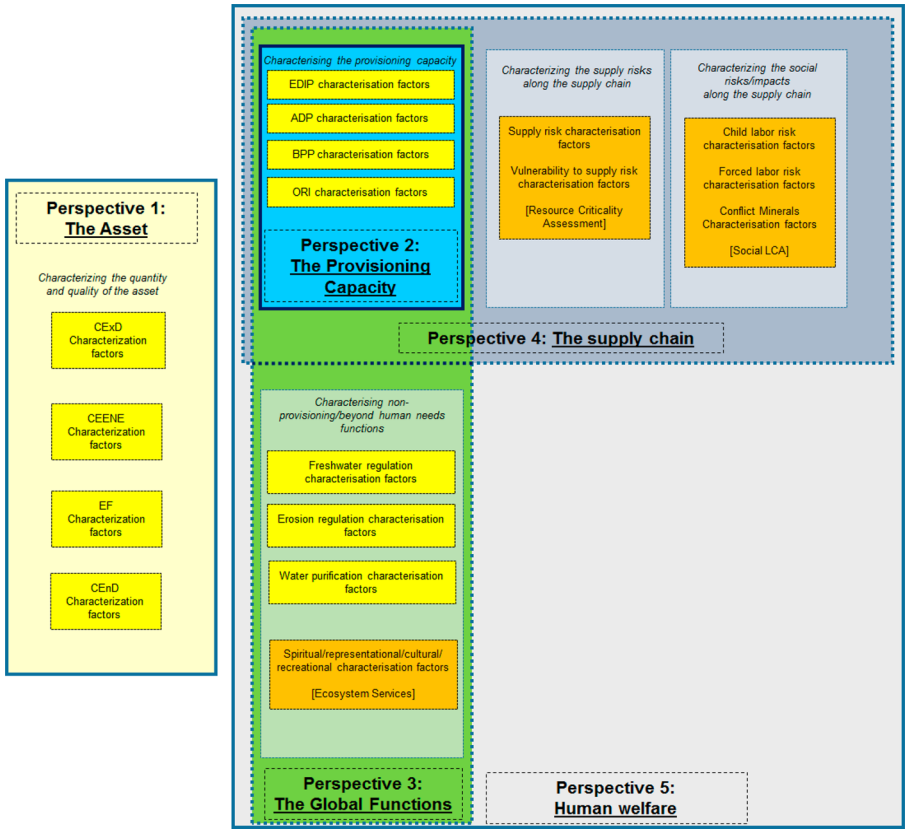


**Figure 3.** Analysis of availability of characterization factors for Natural Resources in function of the adopted perspective. Characterization factors in yellow text boxes are developed in classical LCA, characterization factors in orange text boxes are developed to some extent in best case, but not operationalized in classical LCA. Abbreviations: CExD: cumulative exergy demand; CEENE: cumulative exergy extracted from the natural environment; EF: ecological footprint; CEnD: cumulative energy demand; EDIP: environmental design of industrial products method; ADP: abiotic depletion potential; BPP: biotic production potential; ORI: ore requirement indicator. Notice that EF has a "nearly physical" accounting component of land assets but a virtual component representing the land demand to offset $CO_2$ emissions.

## 3. CURRENTLY USED LCIA CHARACTERIZATION MODELS FOR THE AOP NATURAL RESOURCES: A FIRST ANALYSIS IN FUNCTION OF THE DEVELOPED SAFEGUARD SUBJECTS

Although the AoP Natural Resources have been less well developed and defined than the AoP Natural Environment (Ecosystem Health) and Human Health, many characterization models have been proposed to quantify the impact of production systems on the AoP Natural Resources. Overviews have been given by EC-JRC,[10] Klinglmair et al.,[23] Rørbech et al.[24] and Swart et al.[18] Different classifications have been used, with classification methods starting from the basic (quantification) principle, for example, physical scarcity, various combinations of reserves and extraction rates, exergy, surplus energy, marginal cost, willingness to pay, distance to target, resource accounting, or future decline in ore quality.

When analyzing the available characterization models, it is obvious that Perspectives 1 and 2 are dominant in the LCA community. Within Perspective 1, methods that envisage the impact of a production system on certain natural resource assets are available: they typically account for the quantity of asset withdrawn in terms of physical units. Many of them are intended to cover only a subset of natural resources (SS) due to the fact that the physical unit is not suited to cover all of them, for example, mass cannot capture solar irradiation. A brief overview of accounting methods in function of the particular SS they cover is given in the SI SI2.

With respect to Perspective 2 available characterization methods are more diverse and far less capable to cover different provisioning capacities and involved natural assets. Some methods try to measure the remaining capacity based on (current) use to availability ratios, others try to quantify the decrease in the quality of the remaining capacity in physical or economic terms; and others focus on the (economic) consequences of the phase out of the capacity in the long run. A brief overview of some existing methods within this perspective with their concept, quantification principle and involved natural resource asset(s) are presented in the SI SI3.

Perspectives 3, 4, and 5 are not equally developed and practiced by the LCA community. Basically, the ecosystem services concept can be a proper ground for Perspective 3 (and Perspective 5). First, there are some first cause and effect models onto some specific services beyond provision needs, for example, impacts of (change in) landscape morphology onto esthetic and cultural values and impacts on functional diversity onto ecosystem services damage in general.[25] Apart from this specific cause and effect chain modeling, The Economics of Ecosystems and Biodiversity[26] (TEEB) concept provides a monetization of many functions that could be a base to quantify the impact of withdrawal of natural resources induced by a production system. Also the Natural Capital Project, a partnership between Stanford University, The Nature Conservancy and World Wildlife Fund provides a framework and a tool (InVEST) for the valuation of ecosystem services for


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decision making.[21,27] On the other hand, there are also developments within Perspective 4 that look for the integration of Natural Resources within a LCA perspective (elementary flows based) with socio-economic mechanisms within the human-industrial environment. Resource criticality can be mentioned: the assessment covers the environmental dimension with factors like "depletion of reserves", the economic dimension with factors like "dependency" and "substitutability" and the social dimension with factors like "human right violations" and "child labor".[28−30]

## 4. CONSEQUENCES OF ADOPTING A PARTICULAR PERSPECTIVE

In order to understand the consequences of adopting a certain perspective, essentially one needs to understand the need of the characterization factors of particular natural resources in the respective perspectives. Therefore, we grasped the current available characterization factors when available or at least the framework where they could derived from. The exercise is depicted in Figure 3 and characterization factors are reported in SI SI4 for copper as abiotic stock resource, wood and land. We easily have characterization factors at hand within Perspectives 1 and 2. Characterization factors are available to complete Perspective 3 for some ecosystems services yet applicable in classical LCA (e.g., water purification potential), but also from ecosystem services modeling not yet integrated in classical LCA (e.g., recreational value of crop land is estimated as 4713 USD/ha·yr; see SI SI4). Supplementary to the characterization factors within Perspectives 2 and 3, supply chain characterization factors are required for completing Perspectives 4 and 5, respectively. They are not available from classical LCA, but can be derived from criticality studies and/or methodologies and social LCA, see SI SI4.

From this exercise, a few conclusions of the adoption of a certain perspective can be derived. First, moving away from Perspectives 1 and 2 toward Perspectives 3, 4, or 5 entails an increase in complexity. This shows the need of including characterization mechanisms in LCIA which go beyond the classical focus of environmental LCA. Second, looking at the characterization factors, they are incomplete in order to characterize for example the global ecosystem functions. Third, if they are available, there is a need on a proper merging with classical characterization factors. But maybe the most important conclusion is that a clear overarching and guiding perspective is currently missing in LCA to characterize and assess natural resources. Other frameworks such as ecosystem services evaluation, resource criticality and social LCA are seen to be key methodologies which LCA could borrow from toward more integrated assessments, despite they have different purposes and/or scales of application. In this sense, the paper provides guidance toward a more detailed definition of the concept of "Natural Resources" in LCA and may assist in a better understanding of the positioning of current models and a better identification of missing models and needs of joining models in function of the adopted perspective.

## ■ ASSOCIATED CONTENT

### Supporting Information

Additional information on Detailing the Safeguard Subjects for the AoP Natural Resources S1, S2, and S3 (section SI1), on a brief overview of natural resource accounting methods for the asset of Natural Resources practiced in the LCA community in function of the particular natural resource asset they cover (Section SI2), a brief analysis of existing characterization models fitting within Perspective 2 (Section SI3), and an exercise on characterization factors for copper, wood and land use for crops (Section SI4). This material is available free of charge via the Internet at http://pubs.acs.org/.

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### Notes

The authors declare no competing financial interest.

## ■ REFERENCES

(1) ISO 14044. Environmental management—Life cycle assessment—Requirements and guidelines. International Organization for Standardization: Geneva, 2006.

(2) Finnveden, G.; Hauschild, M. Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in Life Cycle Assessment. *J. Environ. Manag.* **2009**, *91*, 1−21.

(3) de Haes Udo, H. A.; Jolliet, O.; Finnveden, G.; Hauschild, M.; Krewitt, W.; Müller-Wenk, R. Best available practice regarding impact categories and category indicators in life cycle impact assessment. *Int. J. Life Cycle Assess.* **1999**, *4*, 167−174.

(4) Bare, J. C.; Gloria, T. P. Environmental impact assessment taxonomy providing comprehensive coverage of midpoints, endpoints, damages, and areas of protection. *J. Clean. Prod.* **2008**, *16*, 1021−1035.

(5) Dreyer, L. C.; Hauschild, M. Z.; Schierbeck, J. A Framework for social life cycle impact assessment. *Int. J. Life Cycle Assess.* **2006**, *11*, 88−97.

(6) Millennium Ecosystem Assessment, 2005. *Ecosystems and Human Well-being*; Synthesis.Island Press, Washington, DC., 2005.

(7) Valdivia, S.; Ugaya, C. M. L.; Hildenbrand, J.; Traverso, M.; Mazijn, B.; Sonnemann, G. A UNEP/SETAC approach towards a life cycle sustainability assessment—our contribution to Rio+20. *Int. J. Life Cycle Assess.* **2013**, *18*, 1673−1685.

(8) ILCD handbook. Analysis of existing environmental impact assessment methodologies for use in life cycle assessment, 1st edn. EC-JRC (European Commission Joint Research Centre), Ispra, Italy, 2010. http://eplca.jrc.ec.europa.eu/?page_id=86.

(9) ILCD handbook. Framework and requirements for life cycle assessment models and indicators, 1st edn. EC-JRC (European Commission Joint Research Centre), Ispra, Italy, 2010. http://eplca.jrc.ec.europa.eu/?page_id=86.

(10) ILCD handbook. Recommendations based on existing environmental impact assessment models and factors for life cycle assessment in European context. EC-JRC (European Commission Joint Research Centre), Ispra, Italy, 2011. http://eplca.jrc.ec.europa.eu/?page_id=86.

(11) Disability-Adjusted Life Year (DALY). Quantifying the Burden of Disease from mortality and morbidity, WHO, 2014. http://www.who.int/healthinfo/global_burden_disease/metrics_daly/en/.

(12) Maes, J., Teller, A.; Erhard, M.; Liquete, C.; Braat, L.; Berry, P.; Egoh, B.; Puydarrieux, P.; Fiorina, C.; F. Santos-Martín, Paracchini, M.L.; Keune, H.; Wittmer, H.; Hauck, J.; Fiala, I.; Verburg, P.H.; S. Condé, J. P. Schägner, J. San Miguel, Estreguil, C.; Ostermann, O.; Barredo, J.I.; Pereira, H.M.; Stott, A.; Laporte, V.; Meiner, A.; Olah, B.; E. Royo Gelabert, Spyropoulou, R.; Petersen, J.-E.; Maguire, C.; Zal, N.; Achilleos, E.; Rubin, A.; Ledoux, L.; Murphy, P.; Fritz, M.; Brown, C.; Raes, C.; Jacobs, S.; Raquez, P.; Vandewalle, M.; Connor, D.; Bidoglio, G. *Mapping and Assessment of Ecosystems and their Services - An analytical framework for ecosystem assessments under Action 5 of the EU Biodiversity Strategy to 2020*; EU: Luxembourg, 2013; ISBN: 978-92-79-29369-6.

(13) Odum, E. P.; Odum, H. T.; Andrews, J. *Fundamentals of Ecology*; Saunders: Philadelphia, 1971; *Vol. 3*.



DOI: 10.1021/acs.est.5b00734
*Environ. Sci. Technol.* 2015, 49, 5310−5317

(14) How will we know if absolute decoupling has been achieved? Umpfenbach, K.; Bicket, M.; Hirschnitz-Garbers, M.; ten Brinck, P.; Salmons, R.; Tan, A.; Vanner, R.. Dynamix project - Deliverable D.1.2 (Final Draft), 2013. http://dynamix-project.eu/.
(15) *Thematic Strategy on the Sustainable Use of Natural Resources. Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions*, COM/2005/0670 final; Brussels, 2005.
(16) *Roadmap to a Resource Efficient Europe. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.* COM/2011/0571 final, Brussels, 2011.
(17) Bare, J. C.; Gloria, T. P. Critical analysis of the mathematical relationships and comprehensiveness of life cycle impact assessment approaches. *Environ. Sci. Technol.* **2006**, *40*, 1104−1113.
(18) Swart, P., Alvarenga, R. A. F., Dewulf, J. Abiotic resource use. In *Encyclopedia of LCA, Vol. IV: Life Cycle Impact Assessment*; Hauschild, M. Z., Huijbregts, M. A. J., Ed.; Springer Press , 2014; in press.
(19) Steen, B. A. Abiotic resource depletion different perceptions of the problem with mineral deposits. *Int. J. LCA* **2006**, *11*, 49−54.
(20) Swart, P.; Dewulf, J. Quantifying the impacts of primary metal resource use in life cycle assessment based on recent mining data. *Resour., Conserv. Recycl.* **2013**, *73*, 180−187.
(21) Sharp, R.; Tallis, H. T.; Ricketts, T.; Guerry, A. D.; Wood, S. A.; Chaplin-Kramer, R.; Nelson, E.; Ennaanay, D.; Wolny, S.; Olwero, N.; Vigerstol, K.; Pennington, D.; Mendoza, G.; Aukema, J.; Foster, J.; Forrest, J.; Cameron, D.; Arkema, K.; Lonsdorf, E.; Kennedy, C.; Verutes, G.; Kim, C. K.; Guannel, G.; Papenfus, M.; Toft, J.; Marsik, M.; Bernhardt, J.; Griffin, R.; Glowinski, K.; Chaumont, N.; Perelman, A.; Lacayo, M.; Mandle, L.; Hamel, P.; Vogl, A. L. *InVEST User's Guide*; The Natural Capital Project: Stanford, 2014.
(22) Dewulf, J.; Mancini, L.; Blengini, G. A.; Sala, S.; Latunussa, C.; Pennington, D. Towards an overall analytical framework for the integrated sustainability assessment of the production and supply of raw materials and primary energy carriers. *J. Ind. Ecol.* **2015**, In press.
(23) Klinglmair, M.; Sala, S.; Brandão, M. Assessing resource depletion in LCA: A review of methods and methodological issues. *Int. J. Life Cycle Assess.* **2013**, *19*, 580−592.
(24) Rørbech, J. T.; Vadenbo, C. O.; Hellweg, S.; Astrup, T.F. Impact assessment of abiotic resources in LCA: Quantitative comparison of selected characterization models. *Environ. Sci. Technol.* **2014**, DOI: 10.1021/es5023976.
(25) Koellner, T.; de Baan, L.; Beck, T.; Brandão, M.; Civit, B.; Margni, M.; Milà i Canals, L.; Saad, R.; Maia de Souza, D.; Müller-Wenk, R. UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA. *Int. J. Life Cycle Assess.* **2013**, *18*, 1188−1202.
(26) Kumar, P.; Brondizio, E.; Gatzweiler, F.; Gowdy, J.; de Groot, D.; Pascual, U.; Reyers, B.; Sukhdev, P. The economics of ecosystem services: From local analysis to national policies. *Curr. Opin. Environ. Sustainability* **2013**, *5*, 78−86.
(27) Daily, G. C.; Polasky, S.; Goldstein, J.; Kareiva, P. M.; Mooney, H. A.; Pejchar, L.; Ricketts, T. H.; Salzman, J.; Shallenberger, R. Ecosystem services in decision making: Time to deliver. *Front. Ecol. Environ.* **2009**, *7*, 21−28.
(28) Bleischwitz, R.; Bahn-Walkowiak, B.; Ekardt, F.; Feldt H.; Fuhr I..*Resource Politics - New Challenges Demanding New Governance Approaches for a Green Economy*; Heinrich-Böll-Stiftung: Berlin, Germany, 2012.
(29) Erdmann, L.; Graedel, T. E. Criticality of non-fuel minerals: A review of major approaches and analyses. *Environ. Sci. Technol.* **2011**, *45*, 7620−7630.
(30) Graedel, T. E.; Barr, R.; Chandler, C.; Chase, T.; Choi, J.; Christoffersen, L.; Friedlander, E.; Henly, C.; Jun, C.; Nassar, N. T.; Schechner, D.; Warren, S.; Yang, M. Y.; Zhu, C. Methodology of metal criticality determination. *Environ. Sci. Technol.* **2012**, *46*, 1063−1070.


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